Economical Mars Exploration Supported by a Nuclear Thermal Rocket. Steven D. Howe and Robert C. O'Brien, Center for Space Nuclear Research, Idaho Falls, ID, showe@csnr.usra.edu

Introduction: The cost of exploration of Mars is increasing. As launch costs rise and government budgets decline, the frequency of sending probes to Mars decreases. One possible method to increasing the science per dollar is to employ the "mother ship" concept to carry several science platforms to Mars in a single mission and distribute them at their targets independently. This concept is not feasible using standard chemical propulsion but may be possible using a nuclear thermal rocket (NTR). The Center for Space Nuclear Research is pursuing development of tungsten based fuels for use in a NTR.

Between 1955 and 1972 the US built and tested over twenty nuclear reactors/ rocket-engines in the Rover/NERVA programs. The tests of the NTR demonstrated a specific impulse (Isp) of 850 s, a range in thrust from 25 Klbs to 250 klbs, operational duration of over two hours, and the ability to restart multiple times [1]. In short, the program demonstrated the ability to have a core running at 2500 K inside a cooled pressure vessel operating at near ambient temperature. Unfortunately, National priorities shifted away from space exploration and those programs terminated – yet the knowledge that such systems work and what they can accomplish has been invaluable.

In 2007, a National Research Council (NRC) committee was convened to assess the NASA Exploration Technology Development Program (ETDP) [2]. The ETDP contained 22 different projects developing technologies to support the human return to the moon, i.e. the Constellation program. One of the findings of the committee was that the one technological "gap" in the EDTP program was the lack of funding for the NTR.

In 2008, the NASA Mars Architecture Team reported [3] two findings related to nuclear systems: 1) that a fission reactor for the surface was ENABLING for the human mission, i.e. the mission could not be accomplished without it, and 2) the NTR was the PREFERRED propulsion system to carry the human crew to Mars and back.

In 2012, an NRC committee reviewing the NASA Technology Roadmaps identified 16 technologies as high priority out of the 330 reviewed. The NTR was listed as #3. Currently, the Nuclear Cryogenic Stage Program is being supported by NASA which could, possibly, have a ground tested NTR by the end of the decade.

Nuclear thermal rockets offer the potential for high-thrust and high specific-impulse. Many studies during the past few decades have identified missions where the NTR is either enabling or significantly enhances the mission performance. The Center for Space Nuclear Research (CSNR) has begun to reexamine 1) the technology involved in an NTR, 2) the benefits to various missions both manned and unmanned, and 3) the issues in redeveloping a NTR in the current socio-political environment.

Over the past decades, many researchers have recognized the improved capabilities offered by NTRs. Robotic missions to the outer planets benefit from shorter mission flight times and higher payload masses—thus, greater scientific return. Similarly, human missions benefit from shorter exposure to galactic cosmic radiation and higher payloads for life support. Recent studies made at the CSNR have also identified the benefits of using an NTR to support a Lunar Outpost or to intercept an inbound "planet-killing" comet. In addition, the CSNR Summer Fellows program has examined several mission scenarios that benefit from the use of the NTR. One Fellows' study defined a Mars Sample Return mission that could return 100 kgs of samples using a single launch of an Atlas V.

Missions to Mars

The benefits to the human crews on missions to Mars have been delineated by several previous studies [4,5,6]. The primary benefit is the possibility of reduced trip time and, thus, exposure to space radiation. Another benefit is a significantly reduced IMLEO for a given payload mass as compared to a chemically propelled ship. This is, perhaps, more important because, despite desires, payloads will get larger as more equipment and resources are added to reduce risk. Increases in structure or payload mass are multiplied by the propellant mass needed to push them along. The impact on a NTR driven ship is much less than on a chemically driven ship because of the higher specific impulse of the NTR.

While preferred for human missions to Mars, the nuclear thermal rocket (NTR) can also provide an economical method for unmanned Mars exploration by transporting multiple platforms in a single launch. Recent efforts at the CSNR in advanced radioisotope power source development indicate that small power sources ranging from 0.5 to 500 w can be built to power small satellites such as Cubesats. Cubesats can weigh around 10 kg, require 1 to 5 w of electrical power, and contain one or two instruments. Conceptually, a host of such platforms could be packaged onto a NTR upper stage for deployment at Mars. The NTR could either be inserted into Mars orbit for deployment or could eject the platforms during a flyby enroute to other targets in the outer solar system. Each platform could have its own heat shield/airbag entry assembly. This method would allow several platforms to be disbursed on Mars for a single Earth launch.

NTR development

Although NTRs were developed and tested to TRL-6 in the 1960s, changes in environmental laws may make the redevelopment of the nuclear rocket more difficult. Recent advances in fuel fabrication and testing options indicate that a nuclear rocket with a fuel form significantly different from NERVA may be needed to ensure public support.

Because of the desire to reach extremely high temperatures in the reactor core, the Rover/NERVA programs relied on a graphite-based fuel. Consequently, graphite based beaded fuels have the best data base and proven experience. The primary weakness of using graphite is that it must be coated with zirconium-carbide (ZrC) to prevent the graphite from chemically reacting with the hot hydrogen flowing tens of microns away in the flow channels. Cracking of the ZrC led to “mid-band corrosion” which was a major problem for much of the Rover program.

At the time of the Rover/NERVA programs, an alternative fuel form using tungsten cermet composites was also investigated [7]. The GE-710 program in the 1960s and a program at the Argonne National Laboratory (ANL) later, both examined performance of tungsten based fuels for NTR operation. During the GE-710 program, the retention of fission products by the tungsten matrix was demonstrated using static irradiations. The other main advantage of the tungsten fuel form is on the full-power, ground test facility. If the fuel can be shown to not leak radioactivity into the exhaust, then a large, expensive containment facility to scrub out fission products is not required. Use of a smaller test facility could dramatically reduce the program costs.

In 2008, the CSNR undertook a small pioneering project to investigate the ability to fabricate tungsten fuel elements via the relatively new Spark Plasma Sintering (SPS) powder sintering process. By using the SPS furnace at the Idaho National Laboratory, the CSNR fabricated a 19-hole, ¾” across the flats, 3” long, hex cross section fuel element, i.e. the same dimensions as the NERVA fuel element.

Most recently, the CSNR has undertaken a number of activities in collaboration with the Aerojet Corporation to further the development of safe, practical and affordable nuclear thermal propulsion systems. Some of these activities include:

- The assessment and development of low cost ground based testing methods (SAFE) for NTP engines.
- The development of a complete cermet fuel manufacturing and qualification process that can be applied and adjusted to a wide range of element geometries, fuel-to-matrix fractions, and flow channel configurations.
- The testing of cermet thermo-physical and mechanical properties made via the CSNR/Aerojet process in support of accurate computational analyses of NTP system designs.
- Computational modeling of NTP system designs (CFD and neutronics modeling).
- Safety analyses for launch abort and space flight accident conditions.

References

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